How Much Does Wind Energy Access, Transmission, and Intermittency Really Cost?
Supply Curves for Electricity Generation from Wind

Walter Short and Nate Blair
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
walter_short@nrel.gov

Introduction

Recent improvements in the cost and performance of wind power, along with the federal production tax credit and state-level renewable portfolio standards, have encouraged a surge in wind farm development. The American Wind Energy Association (AWEA) estimates that 2,500 MW of wind power capacity will be installed in 2005.[1]

This market penetration of wind power has produced a renewed interest from energy market modelers in more accurately capturing the market potential of wind. Unfortunately, that task is complicated by the site-specific nature of wind power developments. More specifically, modeling wind power market penetration is complicated by the site-specific difficulties of:

- siting wind – environmental and land-use exclusions, terrain slope, population density, road access
- estimating the value of the wind power – impact on utilities' reserve margins, requirement for additional ancillary services, unusable wind generation
- moving the wind power to the load – access to the grid, cost of building dedicated wind transmission lines, opportunities to meet local loads through distributed generation of wind power

With recent improvements, wind turbines can provide power at a bus-bar cost of only 3.5-6 cents per kWh. If the above limitations on wind power are not modeled, most models will predict a surge in near-term market penetration of wind that grossly exceeds reality and that is non-optimal.

Unfortunately, to capture these issues explicitly within an energy market model requires a level of regional disaggregation that most models with a national scope do not possess. Adding such regional disaggregation would greatly expand the computer memory requirements, run time, and complexity of such models. One alternative is to use a supply curve that captures the additional system costs associated with wind as it penetrates into the electric sector—intermittency, transmission, wind resources, site access, etc.

[1] As shown on October 17, 2005, at
http://www.awea.org/news/quarterly_wind_energy_market_outlook_080305.html

The purpose of this paper is to present such supply curves. The supply curves presented here were developed by using the Wind Deployment Systems (WinDS) model. WinDS is a highly geographically disaggregated model with 358 regions (see **Figure 1**) of electric capacity expansion in the continental United States through 2050. It focuses on the technical and market issues that are important to wind energy development—environmental and land-use factors, site access, transmission access and costs, value of wind capacity, ancillary service requirements, etc. The WinDS model is described briefly in **Appendix A** with more detail available at http://www.nrel.gov/analysis/winds .

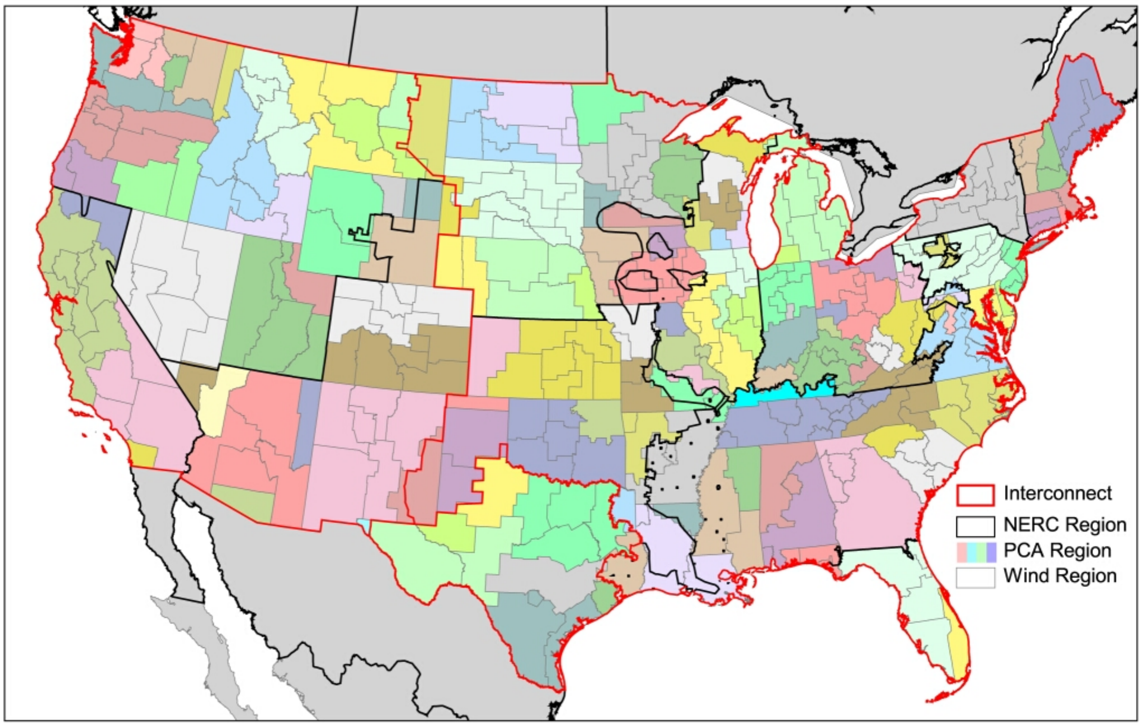

Figure 1: WinDS Regions

The section that follows introduces the general methodology for supply curve development and then describes several different curves and their respective possible applications.

Methodology and Results

To develop a supply curve, we use the WinDS model in two different modes. The first mode is to run the WinDS model as always, i.e. use the full set of disaggregated WinDS regions with restrictions on site access, transmission access and costs, wind capacity value, and ancillary service requirements. With the base case inputs, this produces our base case results for capacity expansion in the electric sector as shown in **Figure 2**. The base case results are characterized by increasing cost of wind generation as the better sites are used up, as longer transmission lines are required for more remote sites, as the capacity value of wind decreases with its penetration into the electric sector, and as more ancillary services are required to support wind generation.

The second mode is to modify the WinDS model to mimic a model with much less regional disaggregation and with much less detail on wind generation. In this second aggregated mode, the costs associated with wind power do not generally increase as the wind penetrates further into the electric sector, because all wind resources have similar costs with no transmission and intermittency impacts. Thus, in this aggregated mode, the cost of using wind to meet electric system loads will be less than the costs in the WinDS disaggregated mode. In addition, the difference in costs between the two modes will grow as wind penetrates further. This difference in costs is the cost to be shown in the supply curve as a function of the level of wind penetration into the market.

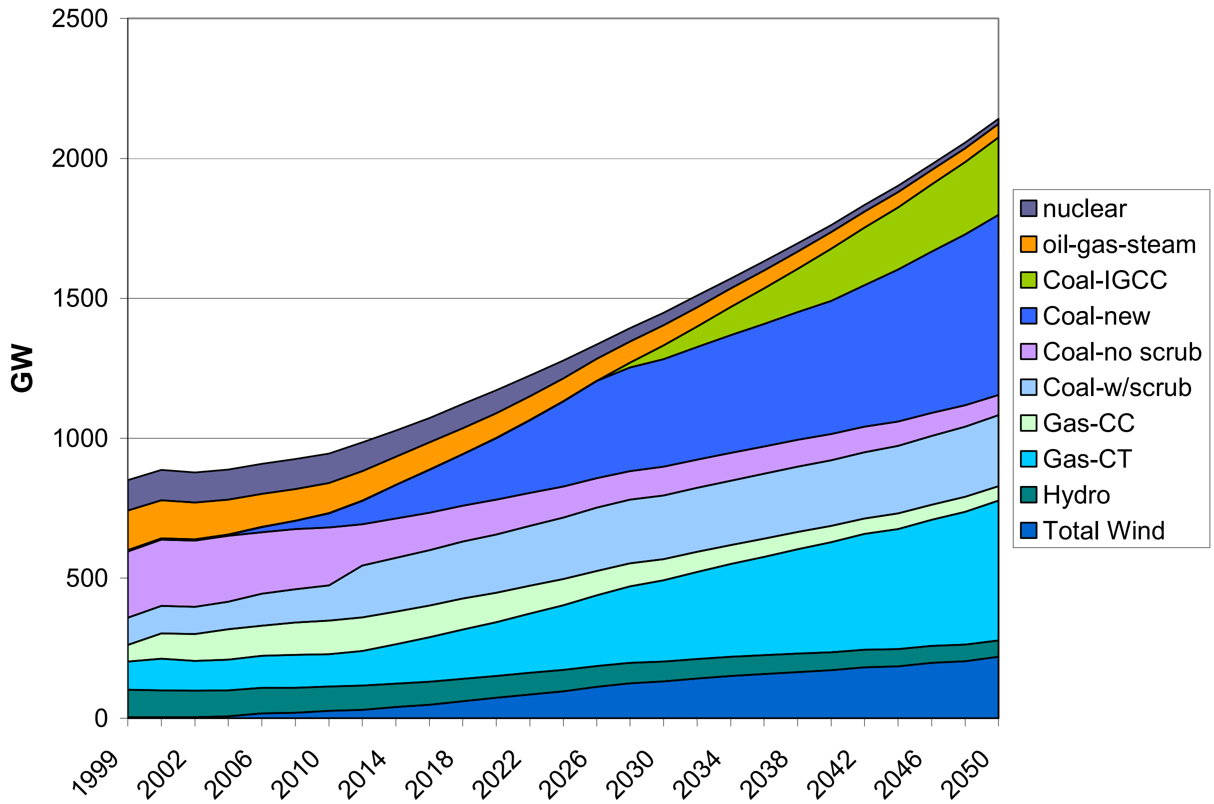

Figure 2: Base Case WinDS Capacity Expansion Results

The differences between the two modes are shown in **Table 1**. These differences consist of cost differences, performance differences, or differences in constraints on wind.

Table 1: Differences in Two Modes of WinDS

Input	Disaggregated Mode/Base Case	Aggregated Mode
Transmission: losses	.024% loss for each mile	None
Transmission: interconnect constraint	Existing transmission lines do not cross interconnects	No restriction
Transmission: boundary constraint	Wind transmitted between regions constrained to line capacity between regions	No restriction
Transmission: access constraint	Wind on existing lines constrained to the capacity available on the line at the point of interconnection	No restriction
Intermittency: Wind capacity value	Decreases with increased penetration of wind, based on correlation between output from different wind sites	Set to capacity factor
Intermittency: Ancillary service for wind	Function of the variance in wind output from all wind farms serving a North American Electric Reliability Council (NERC) region	No impact
Intermittency: Surplus wind generation	Calculated statistically, and based on wind output, system loads, and "must-run" conventional capacity	None
Siting: Topography penalty	2.5% increase in wind capital cost per degree slope	None
Siting: Topography penalty	2% increase in new transmission cost per degree slope	None
Siting: Population penalty	Up to 100% increase in wind capital cost	None
Siting: Population penalty	Up to 100% increase in new transmission capital cost	None

With these lower wind costs and fewer constraints on wind, the aggregated mode of operation of WinDS yields significantly greater wind market penetration than the disaggregated mode as shown in **Figure 3**. However, if in the aggregated mode an additional cost is added to the capital cost for wind in each time period (a different cost for each time period), it should be possible to closely replicate the market penetration of the disaggregated mode.[2] These additional costs are exactly what are needed to construct a supply curve for wind. They represent the additional cost of each MW of wind capacity due to the items shown in Table 1. Furthermore, the cost for each time period is associated with the cumulative wind capacity added in the United States by the start of that period. Thus, the added cost for each period is the supply curve cost. The cumulative wind capacity installed by that time period is the supply curve quantity.

[2] Theoretically, there is no guarantee that an increase in cost can accomplish the same thing in a linear program as the inclusion of a constraint, i.e. there is no guarantee that adding to the capital cost of wind in the aggregated mode can produce the same wind penetration as the disaggregated mode that has additional/different constraints on wind transmission and intermittency. However, with the large number of constraints and variables in WinDS, it should be possible to come almost arbitrarily close.

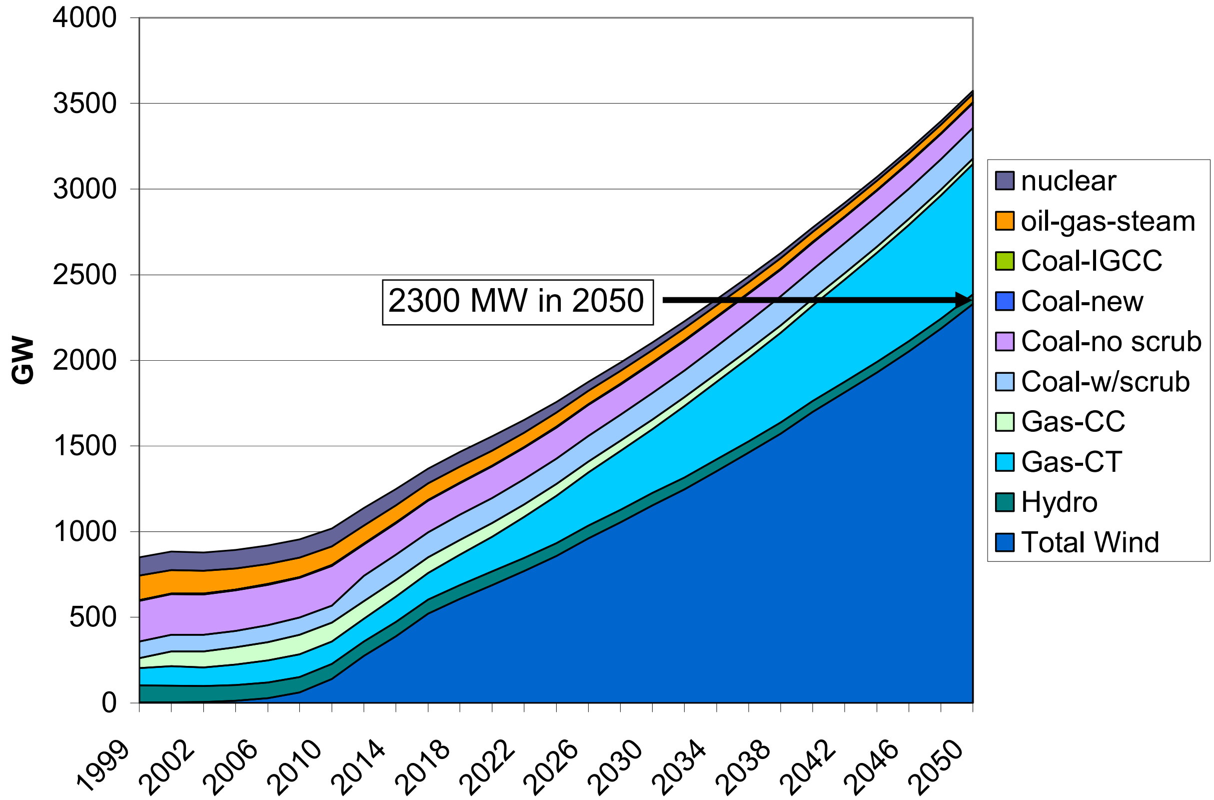

Figure 3: Capacity Expansion in the Aggregated Mode

Figure 4 shows the capital cost addition necessary in each period to reduce the market penetration of the aggregated mode to equal that of the disaggregated mode.[3] These costs were derived by a search routine that exercised the WinDS model in its aggregated mode for each time period, until the cumulative wind capacity of that period came within 2% of the cumulative wind capacity in that period from the disaggregated mode for the base case (i.e. the standard WinDS base case). Once the aggregated mode agrees within 2% of cumulative wind capacity in a period, the next period is addressed in the aggregated mode. The addition to wind capital cost is modified until, once again, the cumulative wind capacity in the new period in the aggregated mode is within 2% of that of the disaggregated mode. Figure 4 also shows that the cumulative capacity of both the disaggregated and aggregated modes are always within 2% of each other.

It was our original intent to separate the cost difference shown in Figure 4 into the portions due to transmission, intermittency, resource quality, etc. We tried several alternative approaches to accomplish this.[4] However, we realized that this is not possible, due to the interactions that occur among these different factors. For example, additional conventional capacity is required in the base case to firm up wind and to make up for wind generation lost in transmitting the wind

[3] The capital cost addition for Figure 4 is zero prior to 2006, because those early periods are constrained to be the same as historical values.

[4] Blair, N.; Short, W.; Heimiller, D. (2005). Reduced Form of Detailed Modeling of Wind Transmission and Intermittency for Use in Other Models: Preprint. 16 pp.; NREL Report No. CP-620-38139.

power. The cost of this additional conventional capacity cannot be divided between transmission and intermittency.

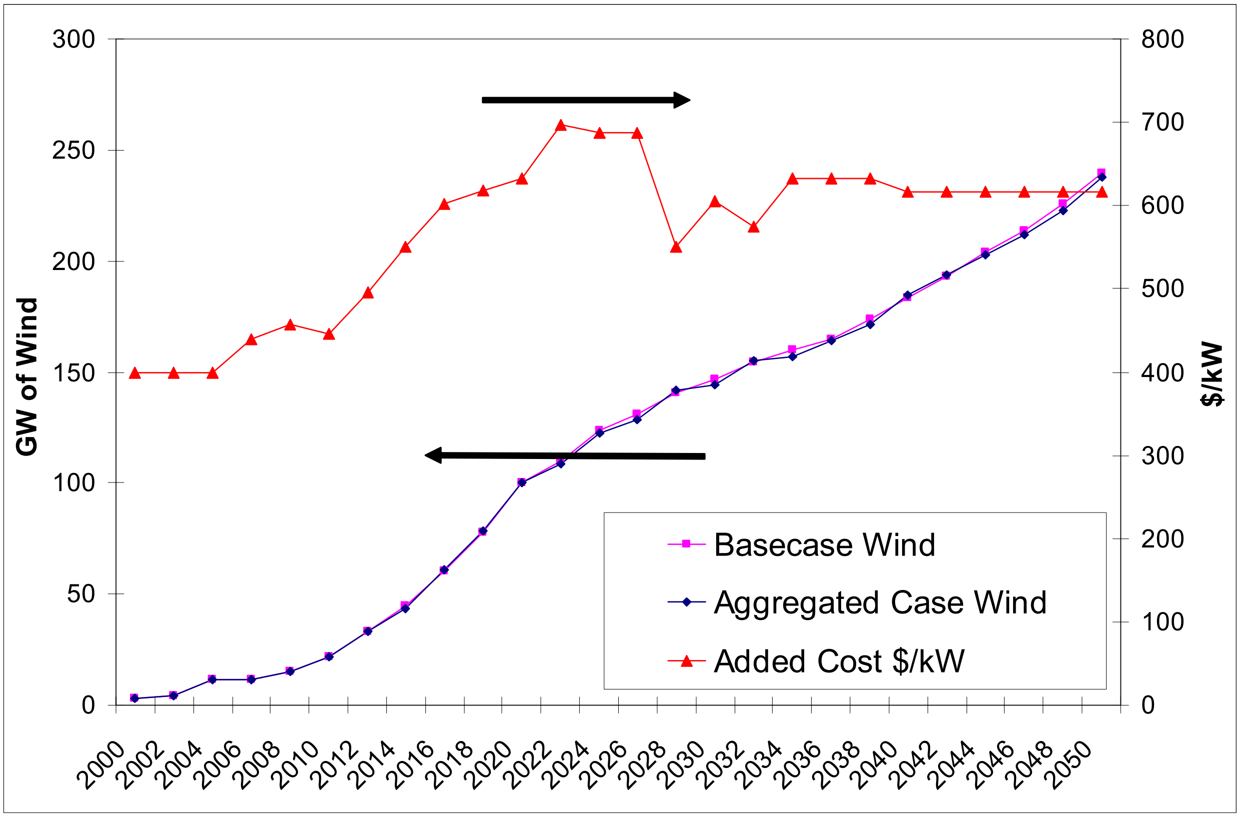

Figure 4: Wind Cost Increases to Force Aggregated Case Equal to the Disaggregated Base Case

In **Figure 5**, we have constructed a supply curve by taking the wind capital cost additions of Figure 4 and replotting them as a function of cumulative wind capacity, not as function of time. As can be seen from Figure 5, the addition to wind capital cost as calculated by our method does not result in a smooth monotonic supply curve. There are several reasons for this. The primary is that we use a search method that moves in discrete increments; the second is that the WinDS model is solved as a linear program, an optimization technique widely known for its “knife-edge” solutions, which can jump from one level of wind capacity additions to another significantly different level with a small change in wind costs. Finally, these cost additions are being applied to wind capacity throughout the country. In some regions of the country, the competition to wind may be tougher (lower cost) than in other areas (lesser competition, i.e. higher costs). Higher-cost wind may penetrate in the higher-cost competition area before lower-cost wind penetrates in the tougher competition area. This can result in a non-monotonic national supply curve that, in some sense, represents the staggered superposition of regional monotonic supply curves.

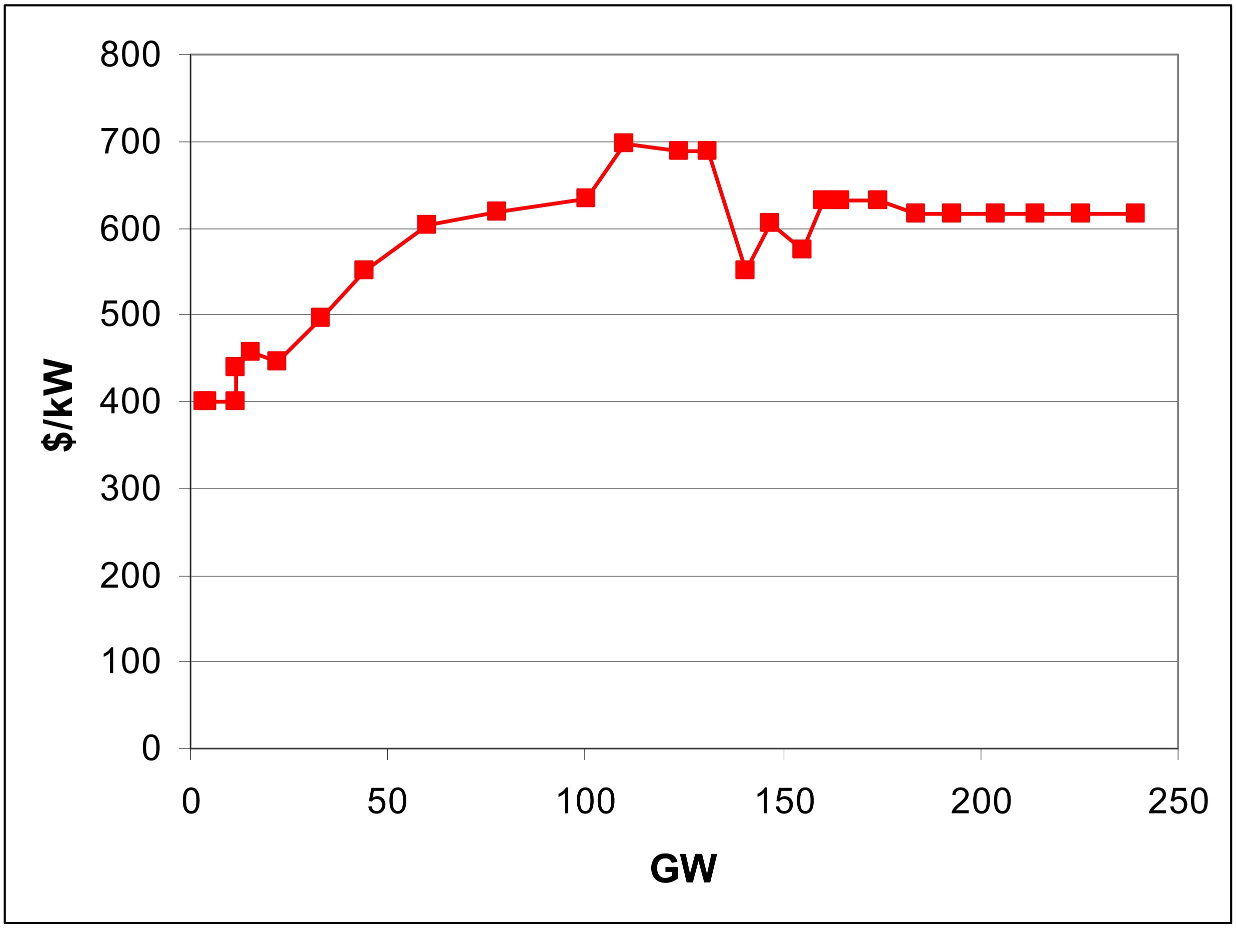

Figure 5: Wind Supply Curve

The supply curve in Figure 5 is based on replicating the base case WinDS results by adding to wind capital costs in the aggregated mode. To determine how robust these results are, we developed the similar supply curve shown in **Figure 6** using a climate change scenario instead of the base case. In other words, we ran WinDS in disaggregated mode with a $100/ton carbon tax, and then replicated the results period-by-period in the aggregated mode by adding both the $100/ton carbon tax and an increment to wind capital costs that is different in each time period. As shown in Figure 6, the base-case-derived supply curve of Figure 5 and the climate-change-case-derived supply curve are quite similar, indicating the supply curve is fairly robust, i.e. the curves derived from these very different cases—base case vs. carbon tax case—are very similar through the full range of the cumulative wind installations of the base case.

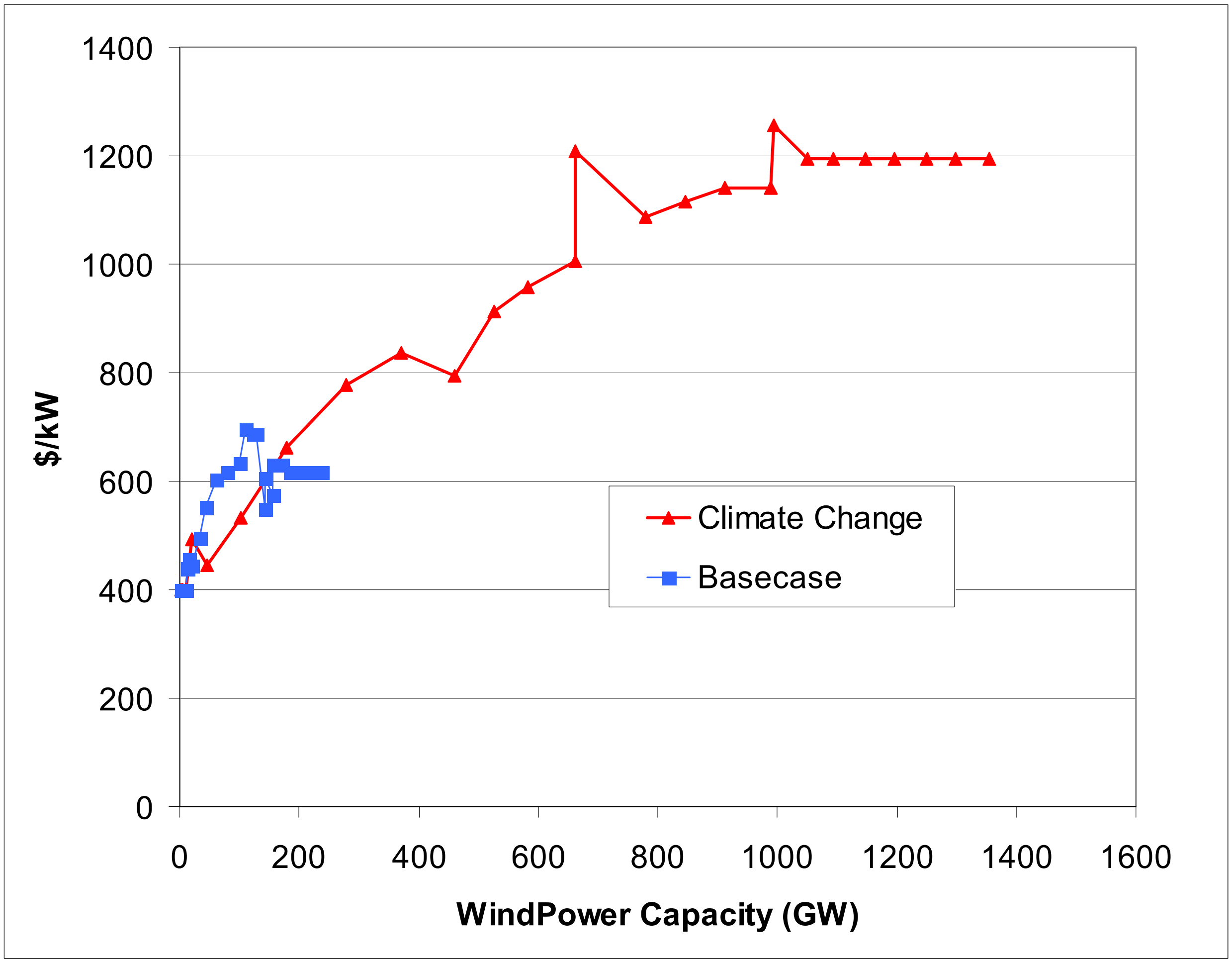

Figure 6: Comparison of Base Case and Climate Change Case Supply Curve

The supply curves of Figure 6 are somewhat unusual in that they don't have the convex shape of a classic supply curve, but rather are concave with the additional wind cost increase slowing as more wind is added. This is due to several factors. First, total wind resources in the United States far exceed the levels deployed, even in the climate change case. So, total wind resources are not being depleted in these curves. On the other hand, the higher-quality Class 6 and Class 7 wind resources are not so plentiful and are being depleted. However, both the aggregated and disaggregated modes capture the wind resource by class, so the curve does not include that resource effect. The abundant wind resources also minimize the impact of other cost factors and limits. For example, one would think that transmission would become an increasingly larger cost as more wind is deployed. It does, but not as fast as one might think. This is because once the penetration level requires that dedicated transmission be built, additional installations can be done for about the same cost, because there is so much raw wind resource available. So, there are no significant additional transmission-cost increases. Similarly, intermittency impacts are dampened by spreading out wind installations so that the correlation between any two wind farms' output is negligible. If one were to construct a scenario in which a much higher fraction of the total wind resource were used, the supply curve would be expected to take a more classical supply curve shape with costs increasing more and more rapidly.

The aggregated mode examined in Figures 4 through 6 includes multiple wind classes. Essentially, WinDS in the aggregated mode uses all the Class 7 wind first, then all the Class 6, etc., because there are no transmission costs or losses in aggregated mode that might make a lower-class wind resource site preferable. We examined a slightly different aggregated mode case in which all wind resources (classes 3 through 7) are assumed to be Class 5. This allows us to construct the supply curve shown in **Figure 7** for use in an aggregated model that doesn't distinguish between wind classes, i.e. has only a single class of wind.

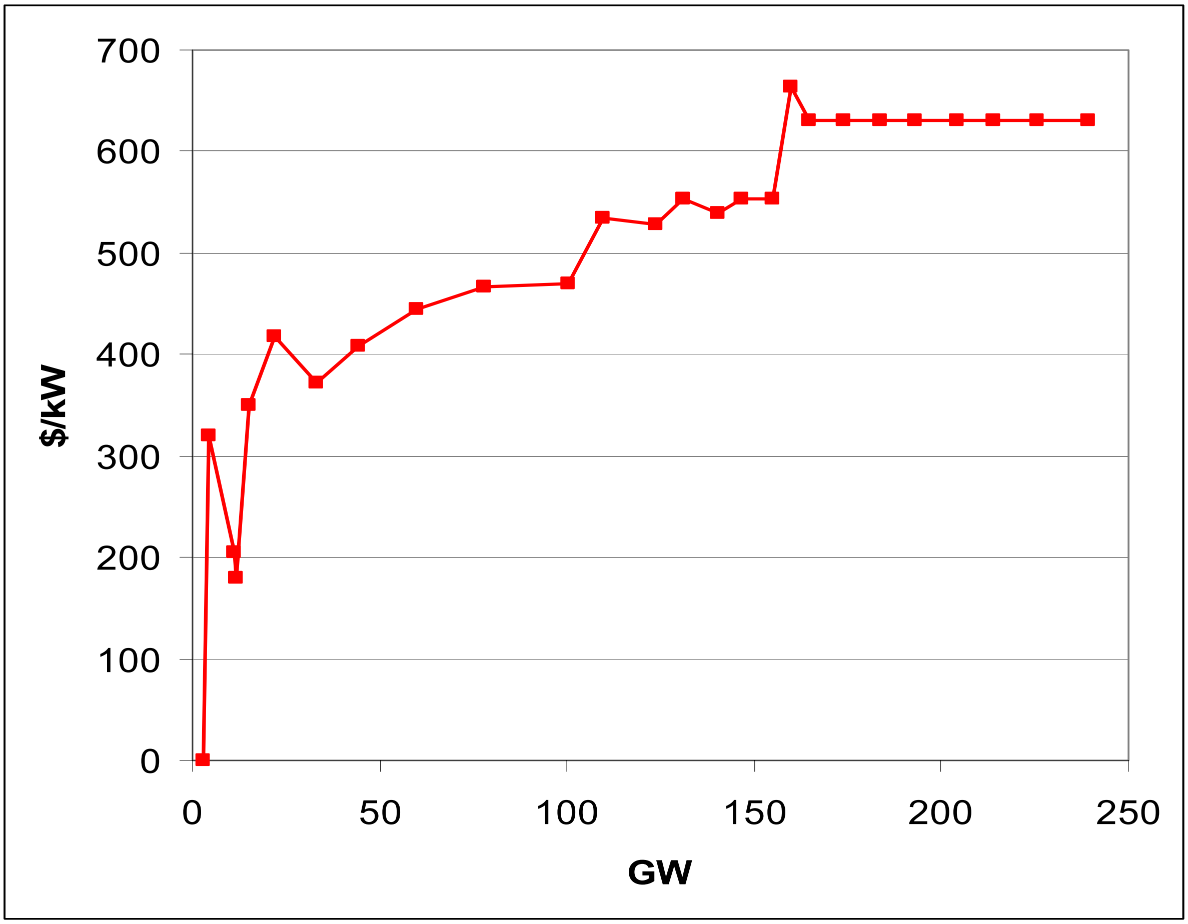

Figure 7: Single-Wind-Class Supply Curve

Note that this single-wind-class supply curve is again very similar to the multi-wind-class curves of Figure 6. The single-wind-class supply curve is lower initially. The Class 5 assumption of the single-wind-class supply curve costs more than the Class 6 and Class 7 wind used initially in the disaggregated mode of the multi-wind-class supply curve. This brings the wind cost from the aggregated mode closer to the generally higher costs of the disaggregated mode. Because the supply curve shows the difference in costs between the disaggregated and aggregated modes, the supply curve costs are lower initially in this single-wind-class supply curve. At higher levels of wind market penetration, the opposite occurs.

Ideally, the supply curve of Figure 5 could be used in a different aggregated model like MARKAL[5] to capture the transmission, intermittency, access, and resource issues associated with wind—without all the detail of the WinDS model. However, the penetration of wind in such an aggregated model may not match that of the base case results from WinDS for several reasons:

- Inputs to the two models may be different
- The models may have entirely different structural assumptions that will result in different outcomes, even with the costs from the Figure 5 supply curve.
- The aggregated model may have a limited range of response due, ironically, to the level of aggregation. If an aggregated model has only one market in which wind can compete, and the competition is "winner-take-all" based on a point estimate of the cost of wind and its competitors, then wind will either lose with no market share or win with 100% market share. In either case, wind would not capture a limited, but non-zero, market share like that which it enjoys in WinDS. Thus, the wind supply curve of Figure 4 is most likely to reproduce results close to those of WinDS in an aggregated model that has a range of possible market-entry levels. This can be effected through some level of regional disaggregation, or through some form of representation of a range of outcomes, e.g., a logit market share that has an implicit probability distribution on all competing prices.

Conclusions

It is possible to build a supply curve for the costs associated with wind deployment. The curves we have developed cover the costs beyond the bus-bar generation costs for wind. This means the supply curve cost can simply be added to another model's estimate of the bus-bar cost of generation from wind. We have qualitatively demonstrated that our supply curve is robust across modeling assumptions, by showing little variation in the supply curves developed under a base case scenario and that developed under a much different scenario that assumes a $100/ton of carbon value. We have developed supply curves for models that have a single region for the entire United States and have either all wind resource classes from Class 3 through Class 7 or simply one wind-resource class. We are currently developing a supply curve for use in models that have multiple regions—like the National Energy Modeling System (NEMS)[6] with its 13 regions—but not the level of regional disaggregation of the WinDS model (358 regions). We also anticipate updating the supply curves as we continue to improve the WinDS model.

[5] As documented on October 17, 2005, at http://www.etsap.org/Tools/MARKAL.htm

[6] As documented on October 17, 2005, at http://tonto.eia.doe.gov/FTPROOT/modeldoc/m068(2004).pdf

Appendix: WinDS Overview

WinDS is a computer model that optimizes the regional expansion of electric generation and transmission capacity in the continental United States during the next 50 years. To do this, it employs a Geographic Information System (GIS) to develop region-specific data for input to a linear program (LP). Most of the methodology description that follows addresses the linear-program portion of the model and is simply referred to as WinDS. Where it is important to distinguish that which is done in the GIS from the LP, the GIS capability is specifically identified.

WinDS minimizes system-wide costs of meeting electric loads, reserve requirements, and emission constraints by building and operating new generators and transmission in 26 two-year periods from 2000 to 2050. The primary outputs of WinDS are the amount of capacity and generation of each type of prime mover—coal, gas combined cycle, gas combustion turbine, nuclear, wind, etc.—in each two-year period. **Figure A-1** shows our base case WinDS generation estimates for the United States for different generation technologies during the next 50 years. These generation estimates correspond to the capacity estimates shown in Figure 2 in the body of this paper.

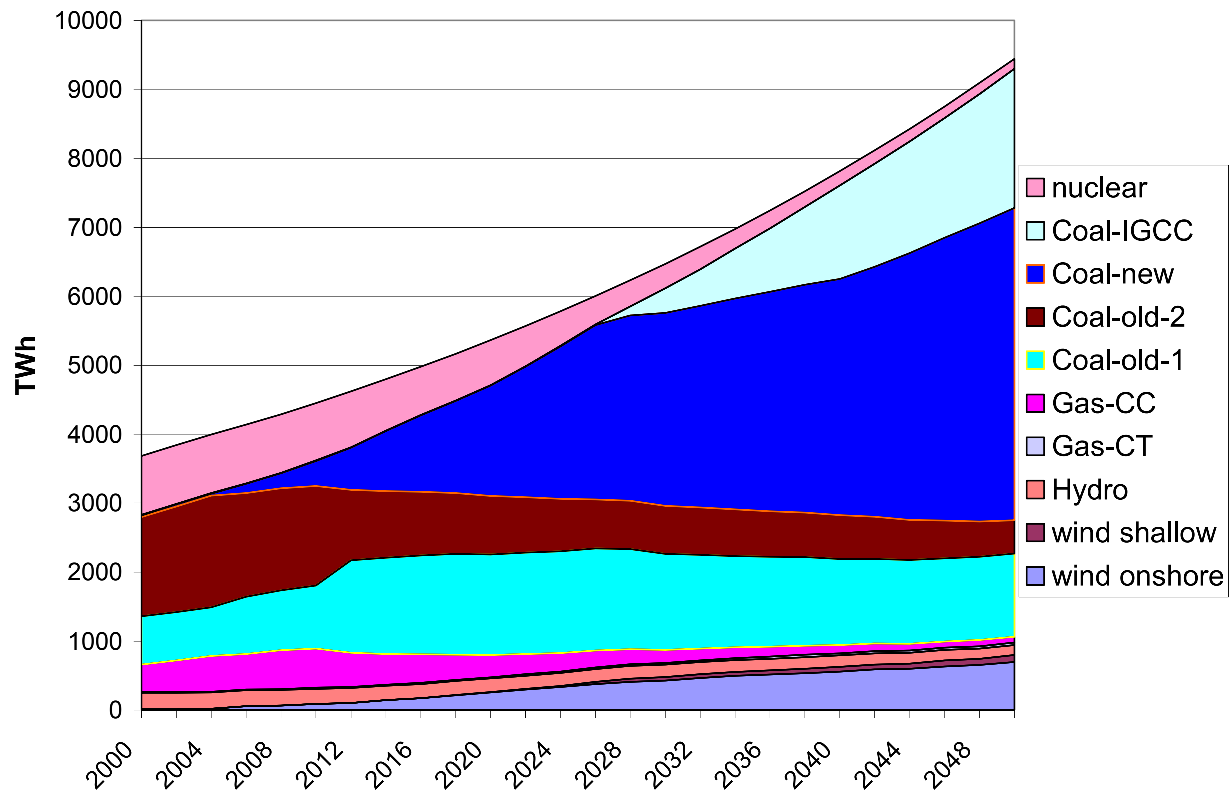

Figure A-1. Base Case WinDS Generation Estimates

While WinDS includes all major generator types, it was designed primarily to address the market issues of greatest significance to wind—transmission and intermittency. The WinDS model examines these issues primarily by using a much higher level of geographic disaggregation than other models. WinDS uses 358 different regions in the continental United States. These 358 wind supply regions are then grouped into three levels of large regional groupings—the power control areas (PCAs), North American Electric Reliability Council (NERC) regions, and national interconnect regions. The WinDS regions were selected using the following rules and criteria:

- Build up from counties (so that electric load can be determined for each wind supply/demand region based on county population).
- Do not cross state boundaries (so that state-level policies can be modeled).
- Conform to PCAs as much as possible (to better capture the competition between wind and other generators).
- Separate major windy areas from load centers (so that the distance from a wind resource to a load center can be well approximated).
- Conform to NERC region/subregion boundaries (so that the results are appropriate for use by integrating models that use the NERC regions/subregions).
- Conform to the three major interconnects within the U.S. grid system (to limit capacity and energy transmission exchanges between the interconnects).

Much of the data inputs for WinDS are tied to these regions and derived from a detailed GIS model/database of the wind resource, transmission grid, and existing plant data. The geographic disaggregation of wind resources allows WinDS to calculate transmission distances, as well as the benefits of dispersed wind farms supplying power to a demand region.

As shown in **Figure A-2**, WinDS disaggregates the wind resource into five classes ranging from Class 3 (5.4 meters/second at 10 meters above ground) to Class 7 (>7.0 m/s). WinDS also includes offshore wind resources and distinguishes between shallow and deep offshore wind turbines. Shallow-water turbines are assumed to have lower initial costs, because they employ a solid tower with an ocean-bottom pier; while deep-water turbines are assumed to be mounted on floating platforms tethered to the ocean floor. For the current analysis, offshore wind was disabled in both the WinDS model and the one-region model (described below).

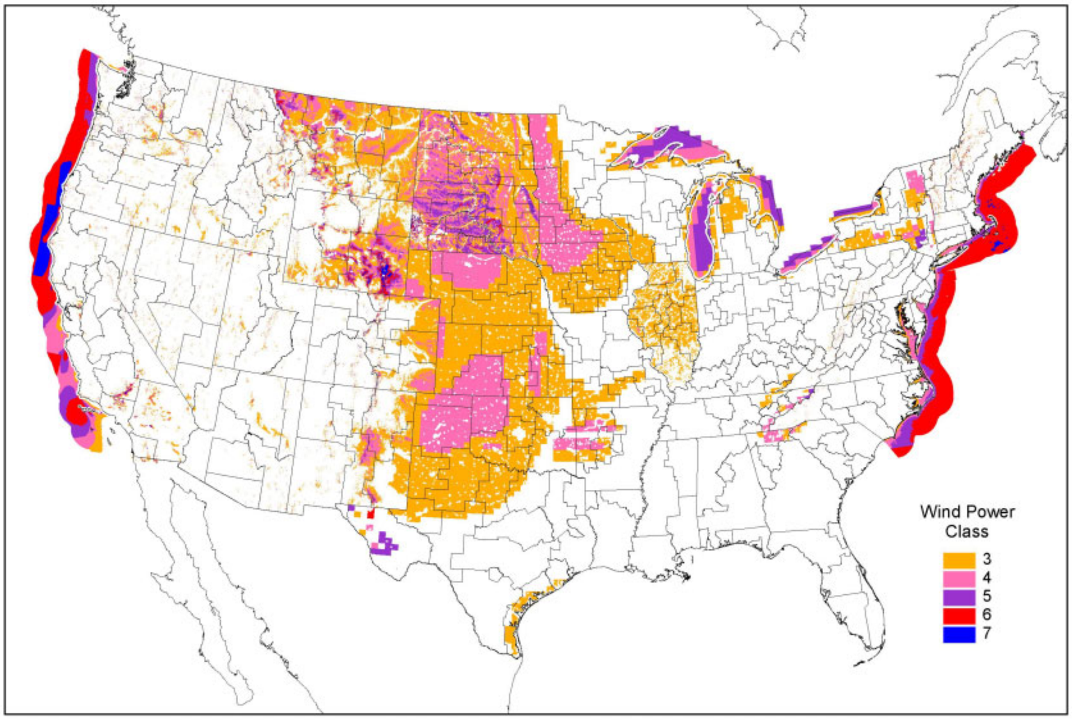

Figure A-2. Wind Resources in WinDS

These different classes and types of wind have different costs and performance characteristics. Generally, the higher wind-class sites (i.e. Class 7) are the preferred sites. However, **Figure A-3** shows that, at any given point in time, the wind turbines installed will be at a mix of sites with different wind-resource classifications. This occurs because, in selecting the installation sites, WinDS considers not only the resource quality, but also factors such as transmission availability, costs and losses, correlation of the wind output with neighboring sites, environmental exclusions, site slope, and population density.

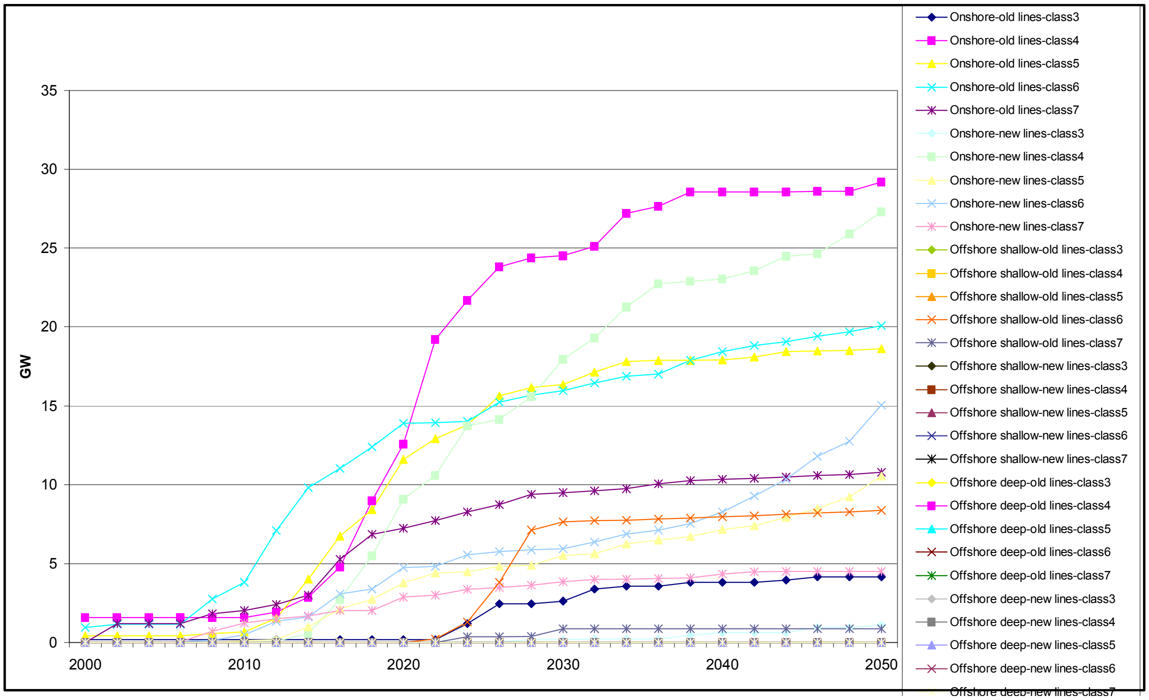

Figure A-3. Wind Capacity Results by Type and Class

WinDS is also disaggregated over time—not only with the 26 two-year periods between 2000 and 2050, but also within each year. Each year is divided into four seasons with each day of each season divided into four diurnal time slices. These 16 time slices during each year allow WinDS to capture the intricacies of meeting peak electric loads, both with conventional sources and intermittent wind generators.

WinDS models the major conventional electricity generators, including:

- pulverized coal
- integrated gasification combined-cycle coal
- existing unscrubbed coal boilers
- existing scrubbed coal boilers
- natural gas combined cycle
- natural gas combustion turbines
- nuclear
- hydroelectricity

Fuel costs are exogenously specified over time by NERC region, as are electric loads. WinDS is a national electric capacity-expansion model, not a general equilibrium model. Assessing the potential of wind energy under any given scenario requires that the scenario be exogenously specified in terms of fuel costs and electric loads by NERC region during the 50-year time horizon of WinDS.

While the focus of WinDS is on wind-energy technologies, the model does include some detail on other generation technologies. For example, there are four types of coal-fired power plants within WinDS—existing boilers without SO_2 scrubbers, existing with scrubbers, new advanced pulverized coal plants, and new integrated-gasification combined-cycle plants. These plants can burn either high-sulfur or, for a cost premium, low-sulfur coal. Generation by coal plants is restricted to base and intermediate load with cost penalties (representing ramping/spinning costs), if power production during peak load periods exceeds production in shoulder-peak hours. Nuclear is considered to be base load. Combined-cycle natural-gas plants are considered capable of providing some spinning reserve and quick-start capability, but the primary source of peak power and operating reserves are combustion turbines and hydroelectricity. Hydroelectricity is not allowed to increase in capacity, due to resource and environmental limitations. Hydro is also energy-constrained, due to water resource limitations.

WinDS tracks emissions from both generators and storage technologies of carbon, sulfur dioxide, nitrogen oxides, and mercury. Caps can be imposed at the national level on any of these emissions. Alternatively, a carbon tax can be imposed that linearly escalates to the maximum tax level over time.